Reliability-Based Optimization of the Inspection Time Interval for Corroded Pipelines.

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Abstract: Non-destructive inspection tools such as magnetic flux leakage (MFL), and ultrasound (UTS) tools are generally used to identify the status of the system (e.g. corrosion defect). However, the inspection data are associated with imprecision and uncertainty due to the imperfect detection and measuring capabilities (i.e. the quality and ability of non-destructive inspection tools in detecting and sizing corrosion defect). In addition, variables such as the defect size, the corrosion growth rate and the failure pressure model used for predicting the remaining pressure strength of corroded pipeline; defect size; and corrosion growth rate are vital variables to be considered in the reliability analysis of corroded pipelines are also affected by uncertainty. To quantify these uncertainties, probability theory has been applied in assessing existing pipelines conditions. The classical probability theorem is used in dealing with uncertainties associated with pipelines reliability and maintenance, inspection time interval, and cost of operations; imprecision also, should be added to these uncertainties for a robust maintenance strategy. Likewise, the failure and maintenance criterion should be based on remaining pressure strength of corroded pipeline that depends on both depth and length of defects rather than maximum defect depth only; and in addition to this, combined simultaneous loadings on the corroded pipeline be given a proper consideration.
A framework with the concept and techniques from classical probability theory is employed for reliability estimates inculcating the impact of inspection and repair activities planned over the service life of a pipeline vulnerable to corrosion. The proposed approach is adopted to solve the optimal inspection interval and the repair strategy that would maintain adequate reliability throughout the service life of the pipeline.
Results obtained for typical pipelines are presented using illustrative numerical efficient algorithm, which serves as an example application to industry-size problems.

Keywords: Imprecise probability, Optimization, Inspection intervals, Corroded pipelines, Combined loadings, Maintenance.

1. Introduction

The scarcity of information associated with the condition of buried pipelines makes the maintenance of such system a challenging task. The inspection and monitoring of these pipelines is necessary in order to ensure their continued fitness for purpose, entails protection from any time-dependent degradation processes, such as corrosion, external interference and ground movement, either natural or man-made. This is necessary because pipeline failures have significant impact on the economic, environmental and social aspects of the society. Therefore, the proper assessment and maintenance of such structures are crucial; negligence will lead to serviceability loss and failure Ahammed and Melchers (1997).

A challenging task is the identification of optimal inspection interval time in order to reduce the overall inspection costs. For instance, areas needing repairs must be accurately pinpointed as to minimise excavations for verifications. This can be achieved in addition to non-destructive inspection tool that have the capability to deliver a consistently high-level of reporting pipeline features and defects, see e.g. (Caleyo et al. 2009); (Hong 1990). Likewise, early observations of failure mechanisms, and determination of the likelihood of failure in association with the pipeline must be handy.

The information obtained from in-line inspection data are imprecise due to the imperfect measurement of defect dimensions and the limited resolution of non-destructive inspection tools. To capture the variability of the data, combination of imprecise probabilities framework with the concept and techniques from classical probability approach is employed in this paper for robust reliability analysis of pipelines. The proposed approach allows inculcating the impact of inspection and repair activities planned over the service life of a pipeline vulnerable to corrosion and combined loadings. This framework is applied to determine the optimal inspection interval and the repair strategy that would maintain adequate reliability level throughout the service life of the pipeline. The reliability analysis is performed adopting an efficient Monte Carlo procedure (de Angelis 2015) simulation, and implemented in the general purpose software OpenCossan, Patelli et al. (2014).

2. Pipelines Modelling

2.1 Corrosion models

The analysis of the future state of a pipeline, such as failure probability, residual strength, etc., is based on the predicted sizes of the defects which were detected during In-Line Inspection. The defect parameters at a given time, t, for a linear rate of the length and depth of corrosion can be assessed Timashev and Bushinskaya (2010), corrosion rates are assumed as constant values:

$$d(t) = d_0 + v_d.t \quad (1)$$

$$l(t) = l_0 + v_l.t \quad (2)$$

Where v_d and v_l are the corrosion rates in the radial and longitudinal directions, respectively; d_0 and l_0 are In-Line Inspection data for depth and length of defect respectively and *t* represents the time.

The use of interval probabilities is adopted in modelling imprecision in the corrosion rates in this paper. This becomes a necessity because the information available is not sufficient to formulate clear probabilistic models with substantial confidence. An interval, Beer et al. (2013) is a closed bounded set of real numbers [a, b] = {x: a ≤ x ≤ b}. Suppose A is an interval, and its end points are $\overline{A}$ and $\underline{A}$, then $A = [\overline{A}, \underline{A}]$. So for n-dimensional interval vector, $(A_1, A_2, \dots, A_n)$ if A is a 2-dimensional interval vector, then $A = (A_1, A_2)$, and for some intervals $A_1 = [\underline{A_1}, \overline{A_1}]$ and $A_2 = (\underline{A_2}, \overline{A_2})$ such that $\underline{A_1} \le a_1 \le \overline{A_1}$ and $\underline{A_2} \le a_2 \le \overline{A_2}$.

The corrosion defect depth and length, as the most important variables in the failure pressure models were assigned an interval of 150 – 250 mm (defect length), and 0 - 100% as measured defect depth through the nominal wall thickness; representing epistemic uncertainty in the probabilistic procedures.

2.2 Combined loadings

Oil pipelines are required to withstand circumferential and longitudinal stresses produced by operating pressure, external forces and influences, and differences in installation and operating temperature.

The circumferential stress due to internal/operating fluid pressure is estimated Ahammed and Melchers (1997), (Timashev 1982) as:

$$\sigma_{cs} = P_{op}.r/wt \quad (3)$$

$$r = (D - 2wt)/2 \quad (4)$$

P_{op} is operating pressure, r is radius of pipe, D is outside diameter of pipe and wt is the pipe wall thickness.

For longitudinal stresses, these are induced as a result of the pipeline operating pressure and temperature. The effects of Poisson’s ratio from outward radial action of the operating pressure of the fluid, in addition to the temperature deformations resulting from the differences in operation and installation temperatures, and elastic bending of the pipeline causing longitudinal bending stresses due to the influence of external forces cumulates into longitudinal stresses of the pipeline.

Thus, longitudinal stress is calculated as:

$$\sigma_{ls} = \mu\sigma_{cs} - \alpha E \Delta t + \sigma_{bs} \quad (5)$$

For buried pipelines under combined loadings, the longitudinal bending stress is:

$$\sigma_{bs} = \left[\left(6k_m C_d \gamma B_d^2 Ewtr\right)/(Ewt^3 + 24k_d pr^3)\right] + Er\chi \quad (6)$$

μ is the Poisson coefficient, α is the linear expansion coefficient of the metal, E is the Young modulus, Δt is the design temperature differential, σ_{bs} is the longitudinal bending stress. B_d is width of ditch at the pipe top level; C_d is coefficient of earth pressure; k_m is bending coefficient depending on load and soil reaction; k_d is deflection coefficient; γ is soil density; χ is longitudinal curvature of the bent pipe; r is internal pipe radius.

The underground pipelines are subjected to both longitudinal and circumferential stresses and these are described as a function of the applied load with the aid of a mechanical model using von Mises equivalent stress expression:

$$\sigma_{es} = \left(\sigma_{cs}^2 + \sigma_{ls}^2 - \sigma_{cs}\sigma_{ls}\right)^{0.5} \quad (7)$$

σ_{es}, σ_{cs} and σ_{ls} are von Mises equivalent stress, circumferential stress and longitudinal stress respectively.

3. Remaining Life of Pipeline

The assessment of the extra stresses induced by the corrosion defects in connection with the design failure pressure for the geometric parameters of a single surface corrosion defect using the DNV-101(DNV 1999) is estimated in the form of:

$$P_f = 2wt\sigma_f/(D - wt)[(1 - d/wt)/(1 - d/wtM)] \quad (8)$$

$$M = \sqrt{\left(1 + 0.31(l^2/D.wt)\right)} \quad (9)$$

Where, P_f = failure pressure, d = corrosion maximum depth, D = pipe outside diameter, σ_f = flow stress, M = Folias' factor, and wt = pipe wall thickness.

The limit state function (LS) for the effects of combined stresses/loadings is defined as the difference between the yield stress of the pipe material (SMYS) and the equivalent stresses σ_{es}, expressed mathematically as:

$$LS_1 = SMYS - \sigma_{es} \quad (10)$$

For the effect of stresses due to corrosion, we have the limit state function to be:

$$LS_2 = P_f - P_{op} \quad (11)$$

Probability of failure (PoF) for the pipeline is written as:

$$PoF = P(LS \leq 0) \quad (12)$$

The failure of the pipe occurs when its resistance falls below the operating pressure, P_{op}. This is after treating the pipe section geometrical properties, corrosion growth rate, material properties, operating pressure and the defect dimensions as random variables to quantify the associated uncertainty in the pipeline system.

4. Pipeline Optimal Time of Inspection and Repairs

4.1 Inspections

Probability of detection is taken as the exponential probability distribution for the detectable depth. Consequently, the average depth of the detectable defects is the reciprocal of quality of the inspection tool. The probability of detection (Pandey 1998) is:

$$PoD = 1 - e^{-qd} \quad (13)$$

Where d = defect depth, q = quality of inspection.

4.2 Repairs

The failure pressure safety factor often defines the repair criterion (Pandey 1998); which is the ratio of the failure pressure (burst pressure) and the Maximum Allowable Operating Pressure (MAOP). A defect will be considered critical and needs to be repaired or removed from the pipeline if the safety factor for the given defect is lower than the threshold: $1.25 \leq SF_{P_f} \leq 1.5$.

$$SF_{P_f} = P_f/MAOP \quad (14)$$

4.3 Optimization formulation

In order to arrive at a safe and economic solution to an overall optimization problem without compromising the objective of acceptable level of safety being ensured and the economic efforts to be reasonable; and without misperception of the safety and economic level, all uncertainties inherent in the problem have to be considered in a realistic manner and be processed with numerically efficient techniques, see e.g. Enevoldsen and Sorensen, (1994). The total cost of operation is formulated and adopted as a deterministic substitute optimization problem as:

$$\min_{N_I,t,e,d} C_T(N_I,t,e,d) = C_I(N_I,t,e,d) + C_R(N_I,t,e,d) + C_F(N_I,t,e,d) \quad (15)$$

$$s.t.\ \beta = P_F(T) \quad (16)$$

Where N_I, t, e, and d denote the number of inspections in the remaining lifetime, time interval between inspections, qualities of inspection, and the number of repair actions based on the measured corrosion defect possible; C_T, C_I, C_R and C_F are the expected total cost of operation, expected costs of inspection, repairs and failure respectively.

$P_F(T)$ is the probability of failure at the expected lifetime.

4.4 Cost of inspection

The expected inspection cost is calculated as the product of the unit inspection cost corrected by the discount rate and the probability that inspection takes place, Enevoldsen and Sorensen (1994). This expected cost is expressed in mathematical form as:

$$C_I = \left[\left(c_I(q)\right)/(1+r)^{T_I}\right](1 - P_F^T) \quad (17)$$

Where $c_I(q)$ is the unit cost of performing inspection of quality q, r is the discount rate and P_F^T is the probability that failure occurs before T_I.

4.5 Cost of repair

The expected repair costs are modelled as:

$$C_R = \sum_{i=1}^{N_I} C_{Ri} \,.\, P_{Ri} . [(1)/(1+r)^{T_I}] \quad (18)$$

Where ith term represents the capitalized expected repair costs at the ith inspection; C_R, is the cost of a repair at the ith inspection and P_{Ri} is the probability of performing a repair after the ith inspection when failure has not occurred earlier.

4.6 Cost of failure

The total capitalized expected costs due to failure are determined from:

$$C_F = \sum_{i=1}^{N_I+1} C_F(T_I).\{P_F(T_I) - P_F(T_{I-1})\}\,.\,[(1)/(1+r)^{T_I}] \quad (19)$$

$C_F(T)$ is the cost of failure at the time T.

5. Example Application

In order to illustrate the application and the advantage of the proposed method, a real life pipeline is chosen for this analysis. Its parameters are listed in Table 1. The radial and longitudinal corrosion rates were assumed to be constant over the elapsed life of the pipeline; and the values are taken to be 0.5mm/yr for both.

The active corrosion defects are 3mm and 200mm for depth and length respectively. The pipeline outside diameter = 609.6mm; wall thickness = 9.52mm; and the operating pressure = 4.96MPa. Other material properties of the pipeline are as follows: type is X52, yield stress is 358MPa, and the tensile strength is 496MPa. The parameter associated with the PoD: the quality of inspection is 3.262. The target lifetime of the pipeline is 50years and the inspection time is chosen within the interval of 0year and 25years. The costs associated with inspection, repair and failure are set as multiplicative factor C_I = 0.018, C_R = 0.243 and C_F = 36.55, see e.g. Gomes and Beck (2014); these factors are multiplied by a unitary cost representing the cost of production and installation of one unit length of pipe, expressed in monetary units. The discount rate is taken as 0.05.

Monte Carlo simulation is employed to simulate the evolution of the system over the time considering inspections and reparation. Large number (4×10^5) of system evolution histories is simulated. The simulation approach has been implemented into OpenCossan - the open source engine of COSSAN software for uncertainty quantification and risk management (Patelli, et. al. 2014).

Simulations were completed using 400,000 samples, varying the number of inspections from 1 to 25 in a time period of 25 years.

Table 1. Stochastic model used for the corroded pipeline.

Variable	Unit	pdf	Mean	CoV
Diameter	mm	N	609.6	0.02
Defect depth	mm	N	3	0.1
Wall thickness	mm	N	9.52	0.02
Ultimate Tensile Strength	MPa	LN	496	0.07
Pipe Yield Stress	MPa	N	358	0.07
Defect length	mm	N	200	0.1
Operating Pressure	MPa	LN	4.96	0.1
Radial rate	mm/yr	LN	0.5	0.10
Long. rate	mm/yr	LN	0.5	0.10

6. Results and Discussion

The total operation cost depends on the number of inspections in the remaining lifetime of the pipeline; time interval between inspections; qualities of inspection; and the number of repair actions based on the measured corrosion defect. This is performed adopting an efficient Monte Carlo procedure simulation. Fig. 1 shows the failure pressure safety factor threshold. Any pipe defects above the threshold based on the sizing of the inspection method are to be excavated and repaired. While the undersized pipe defects will be left unrepaired.

In Figs. 2 and 3, for early inspections, the total cost of failures and repairs are higher; which signifies that increase in numbers of inspection increases the chances of failures to be detected, thereby increasing the total cost of operation.

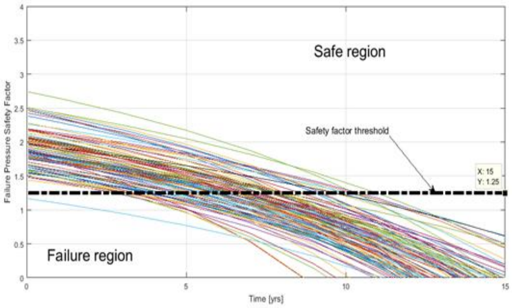

Figure 1. Repair criterion based on failure pressure safety factor

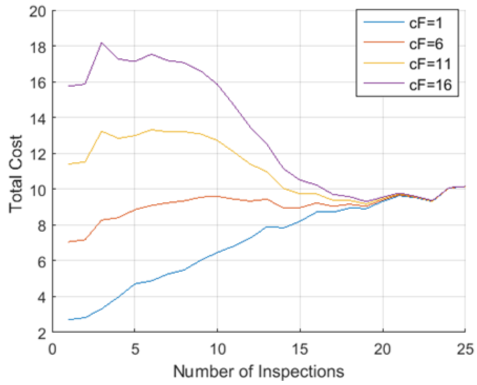

Figure 2. Total cost of operation as a function of varying units of failure cost

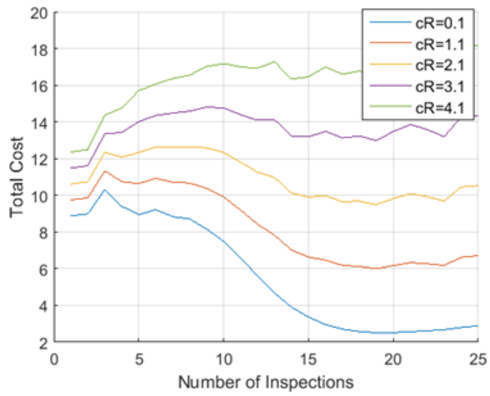

Figure 3. Total cost of operation as a function of varying units of repair cost

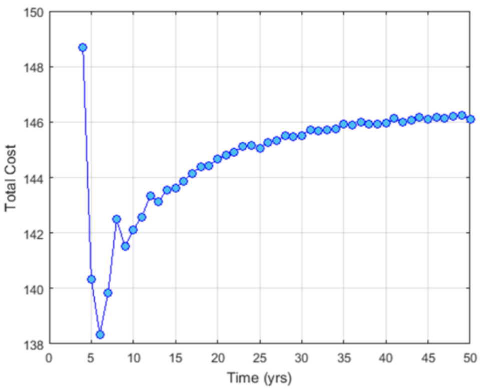

Figure 4. Total cost of operation as a function of time

Fig. 4 shows the total operation cost as a function of time. As the inspection time intervals increase, a large influence on the total cost is seen at the beginning, which later increases and remains constant as from 35years of the pipeline lifetime.

7. Conclusions

The optimal pipeline inspection time allows minimization of expenditures incurred when conducting maintenance activities, and at the same time keeping the pipeline in safe operation mode.

The probabilistic framework presented is well suited for use to determine the optimal inspection interval and the repair strategy that would maintain adequate reliability throughout the pipeline service life.

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